ON THE CHROMATIC ABERRATION OF THE THIRTY-SIX-INCH REFRACTOR OF THE LICK OBSERVATORY.

BY JAMES E. KEELER.

During the summer of 1889, while engaged in spectroscopic work with the thirty-six-inch equatorial, I made a number of rough determinations of the position of the focus of the object-glass for different colors, as an aid in adjusting the spectroscope. Since then I have repeated the measurements more carefully, and at a sufficient number of places in the spectrum to give an accurate determination of the "color curve" of the objective. The peculiarities of every very large or otherwise remarkable telescope are interesting, and even important, in view of their bearing on the future development of instrumental astronomy, and I have therefore arranged the results of the above-mentioned observations in a convenient form for reference and given them in the accompanying tables.

The method of studying the chromatic aberration of a telescope by means of a spectroscope, is sufficiently familiar to astronomers and physicists,* but it is not explained in the text-books, and no apology seems to be required for giving a short description of it here.

An achromatic object-glass is popularly supposed to bring light of all colors to the same focus, and this assumption is also made in the ordinary formulæ for lenses, which deal with first approximations only. It is, however, so far from being strictly true, that in very large telescopes the error is a source of considerable annoyance, and opticians have sought to diminish the false color of the image by giving the object-glass an unusually great focal length—thus reverting to the practice of the sixteenth century astronomers, who were acquainted with no other method for reducing the chromatic aberrations of their single object-glasses. In the thirty-six-inch equatorial of the Lick Observatory the difference of focal length for different colors amounts to several *inches;* nevertheless, it will be shown that this great range is not proportionally greater than in small telescopes, and is as small as the nature of the materials from which the object-glass is constructed will permit.

If a small spectroscope, having so low a dispersion that the whole

* It is due to Prof. H. C. VOGEL, and is described by him in *Berichte der k. Akademie der Wissenschaften zu Berlin*, 29 April, 1880. There is also an excellent though short account in Dr. GILL's article, "Telescope," in the last edition of the *Encyclopædia Britannica.*

spectrum is within the limits of the field of view, is adjusted in the axis of a great telescope so that its slit is in the principal focal plane of the objective, and the telescope is directed to a star, the spectrum of the latter will not be a mere colored line of light, as it would be if the star image were formed by a reflector, but a curious spindle-shaped surface, somewhat resembling the outline formed by a thin vibrating rod with two fixed nodes. The breadth of the spectrum at any place is the diameter of the cone of rays having that particular wave-length, at its intersection by the plane of the slit, and if measured with a micrometer at different parts of the spectrum would give the transverse chromatic aberration in a known plane, and by a simple computation the axial aberration. A simpler method is, however, available. At the two "nodes," or points where the breadth of the spectrum is reduced to zero, rays having the wave-lengths of those parts of the spectrum come to a focus accurately in the plane of the slit. If the spectroscope is moved in or out, by means of the focusing-screw of the great telescope, the "nodes" will travel along the spectrum, retaining always the significance just explained, and if the spectroscope is withdrawn beyond a certain limit, only one node will be visible. If the wave-length of the point in the spectrum at which a "node" falls can be determined, the focal plane for that wave-length is known, being the plane of the slit, and the reading of the draw-tube scale, if the telescope is provided with one, will be a record of its position. Readings should be taken with the nodes in a number of different positions.

A bright star, like *Vega*, with a spectrum of the first class, is an admirable object for observations of this kind, since the intensely black hydrogen lines form marks of known wave-length with which the nodes can be brought into coincidence, and they are, moreover, thickly and regularly distributed in the violet, when the observations are most difficult. Between the red and the blue there are no strong lines in the spectrum of such a star, and a star of another class, as *Arcturus*, may be used instead; or the wire of the eye-piece micrometer of the spectroscope (if it has one) may be set at any desired wave-length by the aid of a previously prepared table, and will answer the same purpose as a fixed line in the spectrum.

The position of the "principal focal plane," in the ordinary sense, *i. e.*, for white light, in this system of focal planes for different homogeneous rays, remains to be determined. It will evidently be a *compromise* plane, the position of which will vary slightly for different eyes, and with the nature of the object examined. If the spectro-

scope is provided with a diagonal eye-piece for viewing the slit from behind, the position of the visual focus is very readily determined by first focusing the eye-piece on the slit, and then adjusting the large draw-tube until the best image of a star is obtained. If a diagonal eye-piece is not provided, the prism may be removed, the view telescope brought in line with the collimator, so that the slit is viewed directly, and the observation made as before. The reading of the draw-tube gives the position of the principal focal plane. If the construction of the spectroscope is such that its telescopes can not be brought into line, the position of the visual focus must be determined with a positive eye-piece (the spectroscope being removed), and referred by measurement to the scale of the draw-tube.

In the large spectroscope of the Lick Observatory the collimator is movable in the direction of its axis through a range of four inches, and is provided with a scale. The slit is viewed from behind by a diagonal eye-piece, so that the observations are made with great facility.

The following table gives the mean of a number of determinations made partly with a small spectroscope attached to the draw-tube of the great telescope, and partly with the large spectroscope just referred to, the objectives of which are of Jena glass. In both cases the chromatic aberrations of the spectroscope lenses themselves are too small to appreciably affect the results:

Line or Object.	λ	Distance from F.
		In.
B	6870.	0.00
C	6563.	—0.24
D	5893.	—0.45
Minimum Focus.	5650.±	—0.47
F	4861.	0.00
$H\gamma$	4340.	+1.45
$H\delta$	4101.	+2.76
Visual Focus.	White.	—0.20

In the last column is given the distance of the focal plane for the stated wave-length from the focal plane for the F line; the positive sign meaning that the focus for the given line is longer than for F, the negative sign that it is shorter.

From these observations a formula can be deduced expressing

empirically the focal length of the objective as a function of the wave-length of light, or, more conveniently, a curve may be drawn through points determined by the observations, with abscissæ representing wave-lengths, and ordinates focal distances, which will represent the same relation $F = \phi(\lambda)$ graphically, and this will be the "color curve" sought. It is evident that for a distinct visual image we must have $\frac{dF}{d\lambda} = 0$ for a value of λ corresponding to the *brightest* rays of the spectrum, and the table shows that this is the case, the minimum focus being in the greenish yellow. For a photographic lens we must have $\frac{dF}{d\lambda} = 0$ for a value of $\lambda =$ about 4300, or for those rays which most strongly affect a photographic plate. The determination of the color curve for the photographic objective of the Lick telescope presents many practical difficulties, the focus being within the tube at a place very difficult of access, and the form of this curve must be reserved for a future investigation.

The only other large telescope which (so far as I know) has had its color correction determined in this manner, is the twenty-seven-inch refractor of the Imperial Observatory of Vienna. Two color curves are given for this telescope by Professor Vogel; one with the lenses of the objective separated by about four-fifths of an inch, the other with the lenses nearly in contact, the latter position being the more advantageous. Comparison of this curve with that for the Lick telescope, the ordinates being expressed not in inches, but in fractions of the mean focal length, shows that they are quite similar, the color curve for the Lick telescope rising somewhat more rapidly in the upper part of the spectrum.

The chromatic aberration of the Vienna equatorial was found by Professor Vogel to be proportionally no greater than that of an excellent telescope, also by Grubb, of about ten feet focal length, and hence, although the variation of focus with the color in these great instruments is surprising, we may conclude that it is as small as the nature of the materials at the command of the opticians will allow.

With the aid of the color curve it is easy to compute the radius (ρ) of the circle in which the cone of rays from the object glass intersects a given plane perpendicular to the axis of the telescope. Professor Vogel has done this for the Vienna telescope, giving the radii for the principal Fraunhofer lines, the intersecting plane being supposed to pass through the focus for the F line. The following

table contains his results, as well as the same quantities for the thirty-six-inch refractor:

TABLE GIVING CIRCLES OF CHROMATIC ABERRATION FOR THE LICK OBSERVATORY AND VIENNA REFRACTORS.

	LICK TELESCOPE.		VIENNA TELESCOPE.	
LINE.	ρ IN INCHES.	ρ IN FRACTIONS OF FOCAL LENGTH.	ρ IN INCHES.	ρ IN FRACTIONS OF FOCAL LENGTH.
B	0.0118	.000017	0.0069	.000017
C	0.0055	.000008	0.0039	.000010
D	0.0000	.000000	0.0000	.000000
b	0.0031	.000005	0.0020	.000005
F	0.0118	.000017	0.0082	.000020
G	0.0530	.000078	0.0343	.000084
g	0.0655	.000096	0.0434	.000106

From this table it appears that the chromatic aberration of the thirty-six-inch refractor is smaller than that of the Vienna telescope, Its superiority in this respect does not, however, arise from a better adaptation of the optical parts, but is almost wholly due to the greater ratio of focal length to aperture (19 : 1 for the thirty-six-inch telescope and 15.3 : 1 for the Vienna telescope), the axial chromatic aberration being nearly the same in both.

The great difference of focus for rays of different colors with a large telescope is, as pointed out by Professor VOGEL, particularly embarrassing in spectroscopic work, only a small part of the spectrum being distinctly visible at one time. It also gives rise to some curious phenomena in ordinary visual observation. With the thirty-six-inch refractor, a planetary nebula and its stellar nucleus cannot be seen distinctly at the same time, the change of focus necessary being particularly noticeable if the nebula shows well-marked structural details, as for example the nebula (H IV 37) in *Draco.** I have sometimes been able to discriminate between a small star and a faint condensation of nebulosity in such an object by merely noting the reading of the draw-tube necessary for distinct vision, the telescope itself thus serving as a spectroscope. Stars of the WOLF-RAYET class, which emit light of (roughly speaking) only two definite colors, yellow and blue, present a peculiar appearance in the telescope,

* See *Monthly Notices* R. A. S., Vol. 48, p. 388, *et seq.* The change of visual focus required in this case is $\frac{44}{100}$ of an inch, or $\frac{1}{1500}$ of the focal length.

having two distinct foci separated by about half an inch, and, if bright enough, can be distinguished from ordinary stars merely by the aspect of the image. The visibility of planetary details differing greatly in color from the general surface tint, would doubtless be much affected by the same peculiarity of large telescopes. Thus, a fine blue line on the surface of *Jupiter* would be spread out into a diffuse band of considerable width at the visual focus, and, if faint, would certainly escape detection. Such differences of focus have been noticed in making drawings of *Mars* during the opposition of 1890. This is a subject of importance, and one which has as yet received little attention.

ARE THE PLANETS HABITABLE?

A Lecture delivered before the Catholic University of America, by Rev. George M. Searle.

Having completed our survey of the planetary system in which we live, a question naturally occurs to us, which has occurred to every inquiring mind since the real dimensions of the orbs belonging to it were known. To the great majority of mankind it is, and is rightly, a question of greater interest than any one with which mathematics or physics has to deal; of greater interest, since life is a much higher and nobler thing than machinery, and the spiritual far above the material. This question is, "Are these planets which, like our earth, move in their appointed paths around the sun, and on which there is certainly ample room for a population far greater than what our globe could support, actually inhabited by beings in any way like ourselves?"

Almost every astronomer has probably been asked what his views are on this question, and whether his science has anything to tell us about it. At each successive increase in the size of telescopes, men vaguely hope that with the new optical power it may be possible to discover some signs of sentient, and perhaps even of intelligent, life in the celestial worlds. "How much does this telescope *magnify?*" is always the interesting question to the popular mind. The professional astronomer perhaps is not looking so much for that. He wants to get more light; to see and to delineate faint nebulæ, to follow a comet as far as he can into the darkness of space, in order